zone is established, it induces the midlatitude zonally symmetric responses in temperature and precipitation -- cooling and wetness associated with tropical warmth -- by altering the eddy-driven circulation (Seager et al. 2005a). In the eastern Pacific sector, the zonally symmetric signal is superimposed with a tropically forced stationary wave response that also influences the precipitation over the southwest U.S. A strong stationary wave response is not often found to be associated with the western Pacific and Indian Ocean SST anomalies. This is explained by the weak climatological upper-level absolute vorticity gradient that prevents an efficient excitation of Rossby waves over these two regions. The following are further highlights of first year's work.

GCM simulations of droughts

Analyzing the ensemble-mean responses to SST, the GOGA runs are found to reproduce many post-1959 events with positive or negative precipitation anomalies over the Americas, including the 1998-2002 North American drought. Figure 1a and b show the observed and simulated (GOGA) precipitation anomalies for the January-May season for 1998-2002. The model reproduces not only the dryness over Mexico and the southwest U.S. but also wetness over the northern South America and dryness over the southern Brazil. The model also simulates the variability of precipitation over the Americas on decadal to inter-decadal time scales. Figure 2a, b, and c show the observation and the simulations from the POGA-ML and SCYC runs for the difference in precipitation between the 1976-1998 and 1961-1976 periods. The wetness over Mexico and the southwest U.S. and dryness over the northern South America are reproduced. A notable feature in both Fig. 1 and 2 is the robust "pan-American" precipitation pattern that is dry (wet) over Mexico and the southwest U.S., wet (dry) over the northern Brazil, and dry (wet) over the south-central South America. This pattern is visible in the observation but the large number of samples produced by the GCM ensures its statistical significance.

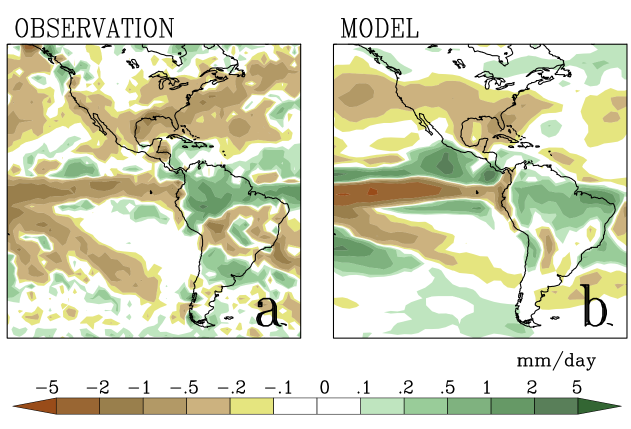

Fig. 1 The precipitation anomalies for January-May from (a) Observation based on the CMAP data, (b) Model simulations as the ensemble mean of the GOGA runs. The anomaly is defined as the 1998-2002 epoch mean minus a 20-yr climatology. Color scale is shown at bottom.

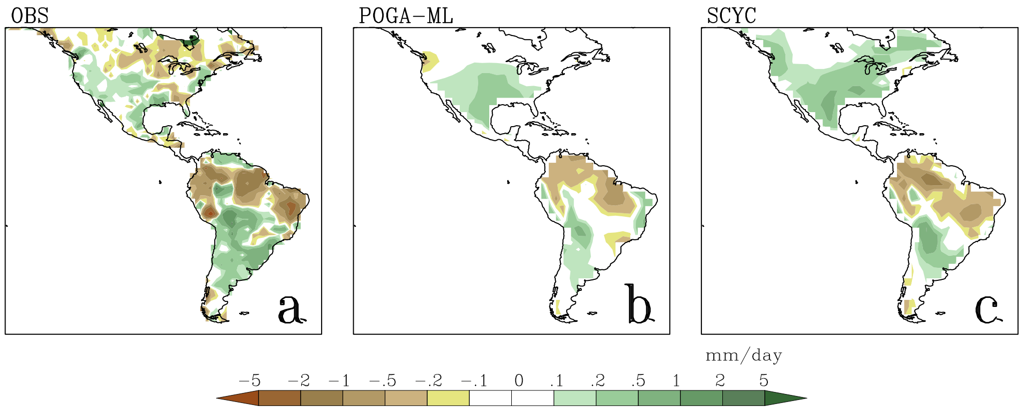

Fig. 2 The interdecadal change in the January-May precipitation, defined as the difference between the 1976-1998 and 1961-1976 epoch means, as deduced from (a) Observation based on CAMS interpolated station data, (b) ensemble mean of POGA-ML simulations, and (c) Twenty-nine year means of the difference between a pair of SCYC runs forced by the averaged seasonal cycle of SST for the two epochs. Only land values are compared due to lack of observations over ocean in the pre-satellite era.

The POGA-ML and GOGA runs are found to produce similar precipitation patterns over the Americas for both multi-year and multi-decadal events, indicating that the Pacific SST anomaly contributes significantly to the precipitation anomalies over land on these time scales. The POGA-ML runs are extended back to the mid 19th century. In the pre-WWII era, the simulated precipitation anomalies over the western U.S. broadly agree with observations based on more limited data, as reported by Seager et al. (2005b). The GCM simulations produce detailed three-dimensional circulation patterns, Complementing the limited upper-air observations, the GCM produces detailed three-dimensional circulation patterns associated with the pre-1950 drought events that will be used to further analyze the SST-drought connection. A comparison of our NCAR CCM3 runs with the GFDL AM2 atmospheric GCM simulations shows an encouraging level of consistency for the simulated precipitation anomalies over the Americas in boreal winter-spring season.

How tropical SST forces the midlatitude responses

Zonally symmetric climate variability

The GCM simulations provide useful clues to the processes that connect the tropical SST forcing to the precipitation anomalies. The tropically-forced extratropical precipitation anomaly is found to have a significant zonal mean component. The superposition of the zonally symmetric anomaly and the tropically-forced stationary waves, along with local moisture feedback -- found to be important over the southwest U.S. -- determine the total precipitation anomalies over the Americas (Huang et al. 2005).

The global, zonally symmetric, climate variability originates from the tropics with a tropics-wide warm (cold) band of tropospheric temperature associated with a warm (cold) tropical SST. The tropical, zonally symmetric, temperature anomaly then induces a secondary response in the extratropics by modifying the eddy momentum fluxes, thereby the eddy-driven circulation in midlatitude. The upward/downward motion associated with the change in the eddy-driven circulation leads to the enhancement/suppression of precipitation (Seager et al. 2005a, Herweijer and Seager 2005). The excitation of the tropical warm or cold band is found to be insensitive to the detail of the tropical SST anomalies. Rather, it depends on the mean condition of the tropical SST. This explains the ubiquitous presence of a common global structure of zonally symmetric circulation and precipitation anomalies on multi-year to multi-decadal time scales.

Tropically-forced stationary waves

The detail of the stationary wave response to the multi-decadal variability of tropical SST is investigated by analyzing the "Rossby wave source" in the GCM simulations. For the inter-decadal (post-1976 minus pre-1976) change for January-May related to Fig. 2, the SST anomaly has multiple positive centers over the tropical eastern and western Pacific and the Indian Ocean. This is reflected in Fig. 3a in the multiple positive centers of anomalous upper-level divergence (due to enhanced convection) over the aforementioned three regions. One of the main processes for the tropical divergence forcing to excite a midlatitude stationary wave response is through the advection of climatological absolute vorticity by the divergent wind, the strength of the process measured by the "Rossby wave source" (RWS, Sardeshmukh and Hoskins 1988). It is found that, despite having divergence anomalies of equal strength, the RWS is weaker over the western Pacific and Indian Ocean but much stronger over the eastern Pacific as shown in Fig. 3b. This is due to the fact that the climatological absolute vorticity has a tighter gradient over the eastern Pacific sector (Huang et al. 2005) as shown in Fig. 3c. This explains why tropically forced Rossby wave trains are frequently observed to emanate from the eastern Pacific (producing a generic "PNA pattern") but much less commonly found to come out of the western Pacific and Indian Ocean sectors. As such, the western Pacific and Indian Ocean SST's do not influence North American droughts by the classical mechanism of forced stationary waves. Their influences on North American droughts, if any, must rely on either their contribution to the tropical mean condition or other midlatitude processes involving transient eddies.

Studies with an aquaplanet model

In Nature and in full GCM simulations, irregular land-sea distribution often create difficulties for a straightforward interpretation of the tropically-forced precipitation anomalies. To isolate relevant physical processes, numerical experiments are performed with an "aquaplanet" GCM that excludes any land mass in the lower boundary but retains the physical processes for precipitation. The model was modified from the NCAR CCM3 AGCM. One of the main purposes of the experiments is to investigate how a zonally symmetric response in atmospheric circulation and precipitation arises from a zonally symmetric or asymmetric tropical SST forcing.

Figure 4 illustrates the setting of one of the aquaplanet experiments. A climatological run is performed with a zonally symmetric SST shown in Fig. 4b. A perturbed run is forced with this SST plus a tropical anomaly, in this case a zonal wavenumber one structure with a maximum of 3°C and no zonal mean as shown in Fig. 4a. The precipitation anomaly is obtained from the difference between the two runs, as shown in Fig. 4c. Even without a zonal mean, the tropical SST anomaly produces a zonal mean response in the tropical precipitation due to the nonlinear relationship between SST and precipitation. Globally, the precipitation pattern exhibits a multiple banded structure, with a non-zero zonal mean response in the midlatitude where the SST anomaly is zero. A preliminary analysis indicates that transient eddies contribute substantially to the maintenance of the extratropical zonally symmetric structures. Following this example, a series of aquaplanet runs are now being performed with different combinations of the zonally symmetric and asymmetric components of tropical SST anomalies. When completed, these experiments will help quantify the relative contributions by these two components of the tropical SST to the extratropical precipitation anomalies relevant to North American droughts.

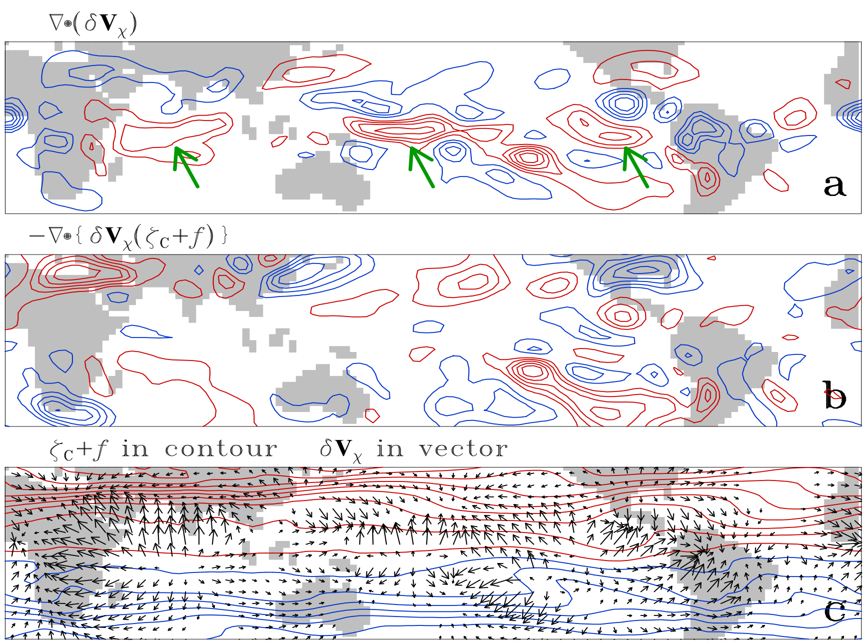

Fig. 3 (a)The interdecadal change (January-May, corresponding to the case in Fig. 2) in the upper-level divergence deduced from the GOGA runs. Major centers of anomalous divergence are indicated by green arrows. (b) Same as (a) but for the anomalous Rossby wave source. (c) The vectors show the perturbation divergent wind corresponding to (a). The contours are the climatological absolute vorticity. All fields shown are at the 200 mb level. Contour interval is arbitrary for (a) and (b) and 0.2Ω for (c), where Ω is the rotation rate of the Earth. Positive (negative) contours are in red (blue).

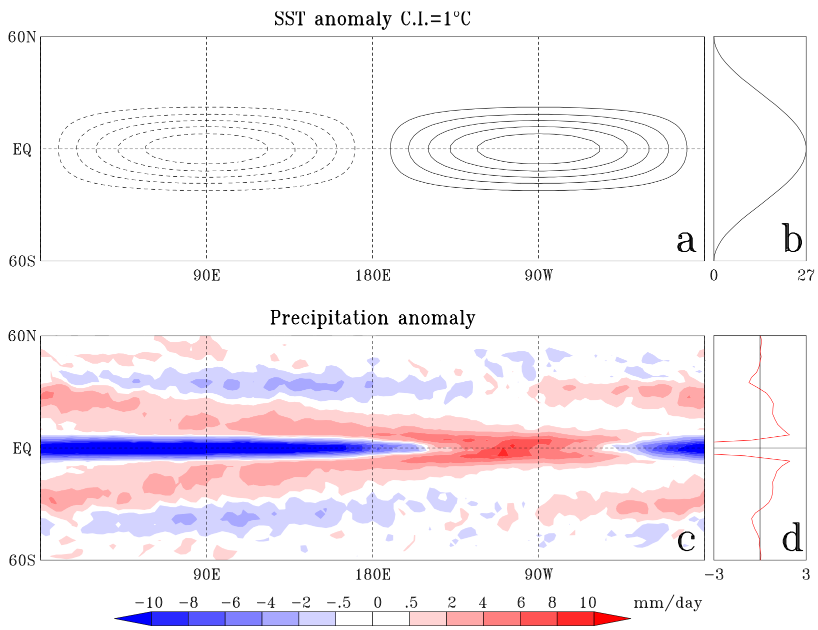

Fig. 4 (a) The SST anomaly for the twin runs of an aquaplanet experiment. Contour interval is 1°C with negative dashed. (b) The profile of the zonally symmetric SST used to force the control run. (c) The simulated precipitation anomaly, with color scale shown at bottom. (d) The zonal mean of the precipitation anomaly in (c). the precipitation anomaly shown in (c). The simulations are performed under a perpetual equinoctial condition.

Statement of work for year 2

During the first year, we have been on target in finishing the planned GCM simulations, preliminary analyses of the influence of different parts of tropical SSTs on the American droughts, and the first stage of the aquaplanet experiments. Thus, our plan and goals for the second year remain unchanged as they were originally proposed. The major work for the second year will consist of

- Further analyses of the impacts of the eastern (EP) and westerm Pacific (WP) and Indian Ocean (IND) SST anomalies on the North American droughts by analyzing the stationary waves, zonally symmetric climate anomalies, and transient eddy responses excited by these components of SSTs in the GCM simulations; Extending the GCM simulations to include a set of SCYC runs with the SST anomalies imposed only in one of the EP, WP, and IND regions.

- Analyses of the precipitation and temperature anomalies over North America in boreal summer simulated by the GCM; Comparisons of the mechanisms of the tropically-forced droughts in summer and winter; Extension of the model inter-comparison for the NCAR and GFDL GCMs to boreal summer.